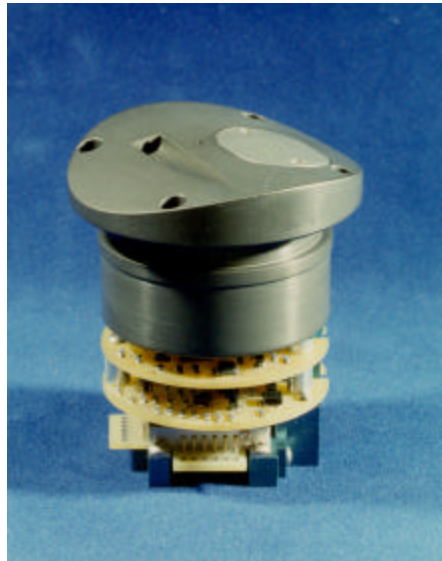




# *Miniature Flow Sensor For Use as a S&A Second Environment Sensor*



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*Making Sea Power 21 a Reality*

# *Differential Pressure Flow Sensor (DPFS)*

## *Purpose*

Measure fluid flow to detect post launch environment for S&As while meeting the following requirements

- Small
- Non-intrusive
- Accurate

Originally developed for torpedo Safety and Arming, but readily adaptable to other applications

# *Differential Pressure Flow Sensor*

## *Features*

Utilizes the principle of Pitot theory, without protruding from the vessel surface

- Performs well in air or fluid media
- Mounts flush to vessel surface: not prone to damage
- Molded plastic or metal housing easily formed to vessel contour
- Can be formed directly in vehicle skin
- Range and resolution tailored via pressure sensor
- Solid state: no moving parts!!



*DPFS integrated into S&A*

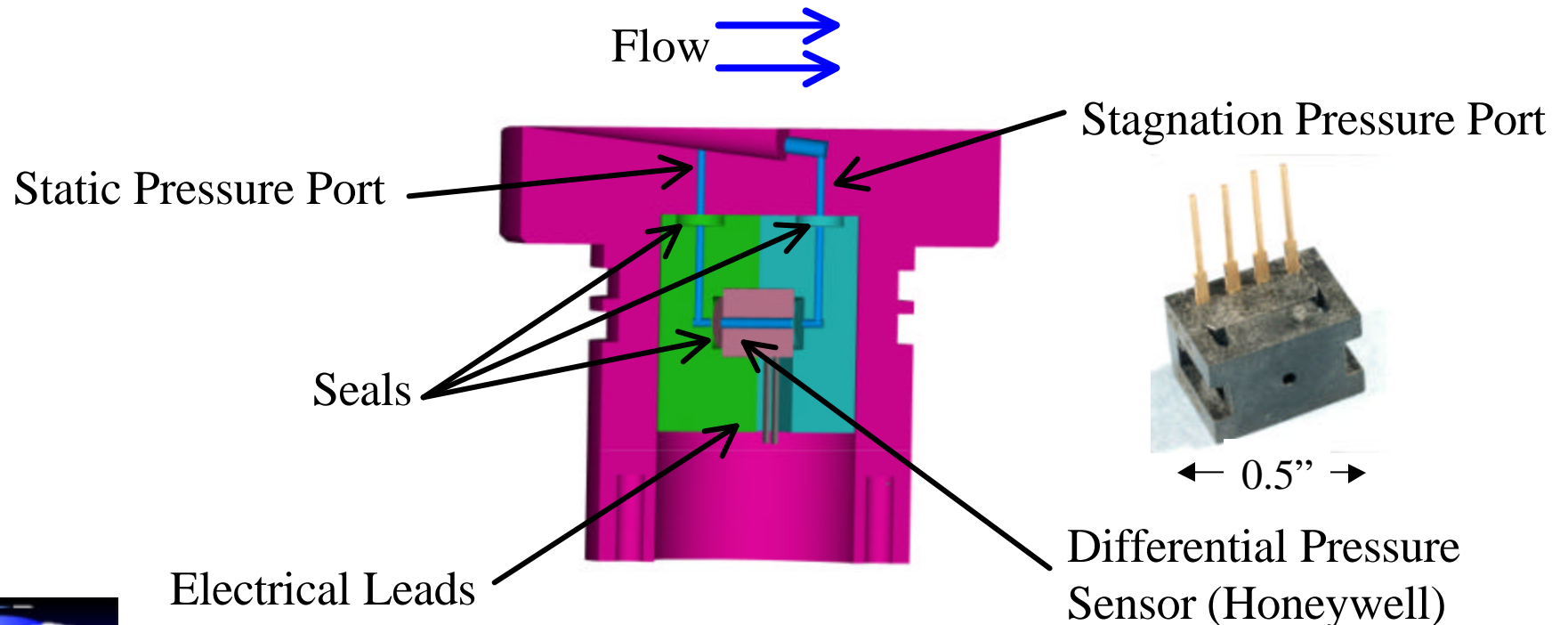
*Accurate, low cost bulk fluid flow or mass flow meter*

# *Differential Pressure Flow Sensor*

## *Flow Sensor Description*

### *Theory of operation:*

Flow over a body is drawn into the flow ports due to viscous force interaction between the body and the fluid. The momentum of the fluid creates a pressure difference which can be sensed by a commercial off the shelf (COTS) differential pressure sensor.



# *Differential Pressure Flow Sensor Design for Application*

## *Application specific requirements*

Environmental  
fluid media  
survivability

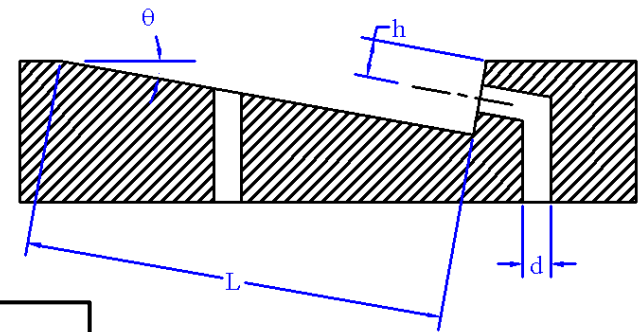
### Performance

Reynolds number  
Range/resolution

## *Design parameters*

### **Pressure sensor selection**

Flow porting configuration  
Ramp profile  
Port orientation  
Port location



## *Costumed configured DPFS design*

Readily adapted to most flow environments

# *Differential Pressure Sensor*

## *Selection*

*Batch fabricated Honeywell MEMS sensor selected for torpedo application:*

### Key selection criteria

- Media compatibility
- Size
- Reliability
- Environmental
- Cost
- Power
- Supply, control, and readout electronics
- Sensor range & resolution
- Adaptability



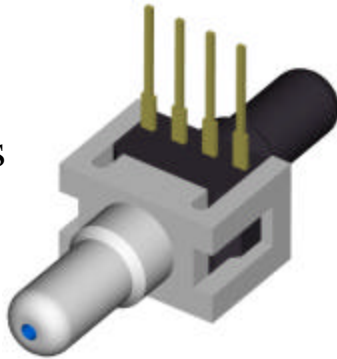
### Honeywell differential pressure sensor

- Compatible with air or water
- **Volume  $< .06\text{in}^3$**
- Silicon diaphragm with embedded piezoresistive elements
- Robust; solid state
- **$< \$20$  in very small quantities**
- **$< 25\text{mW}$  supply**
- Simple supply, control, and readout electronics
- Family of pressure ranges available; resolution sufficient
- Molded housing available in custom configurations

# *Differential Pressure Sensor*

## *Honeywell COTS*

Several  
port  
variations



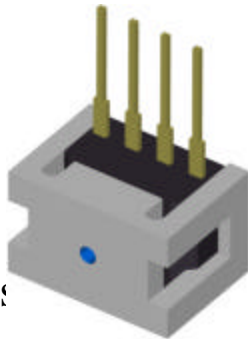
Several  
pressure  
ranges

20mW  
power

Temperature  
compensated

Flow Tunnel Configuration

Novel  
packaging



micro-  
machined  
diaphragm

Embedded  
piezoresistors

Low  
cost

High Pressure S&A Configuration

Molded  
housing



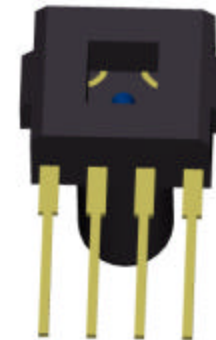
Media  
seal

Silicon  
diaphragm



Conductive  
media seal

Molded  
housing with  
conductors



Sensor Assembly (Exploded)



# *Honeywell Differential Pressure Sensor*

## *Environmental Performance*

- Operating Temperature (manufacturer): -40 to 185°F
- Storage Temperature (manufacturer): -67 to 212°F
- Shock (CTIP program): 1500g 0.3ms shocks
  - 6 axis, 5 shocks/axis, -60°F, ambient, 160°F
- Miscellaneous:
  - Background pressure survivability demonstrated to above 1400psi
  - Compatibility with salt water demonstrated
  - Performance in various operational environments demonstrated

**Honeywell sensor survived all tested environments without significant sensitivity changes**





# *DPFS as a Environmental Sensor*

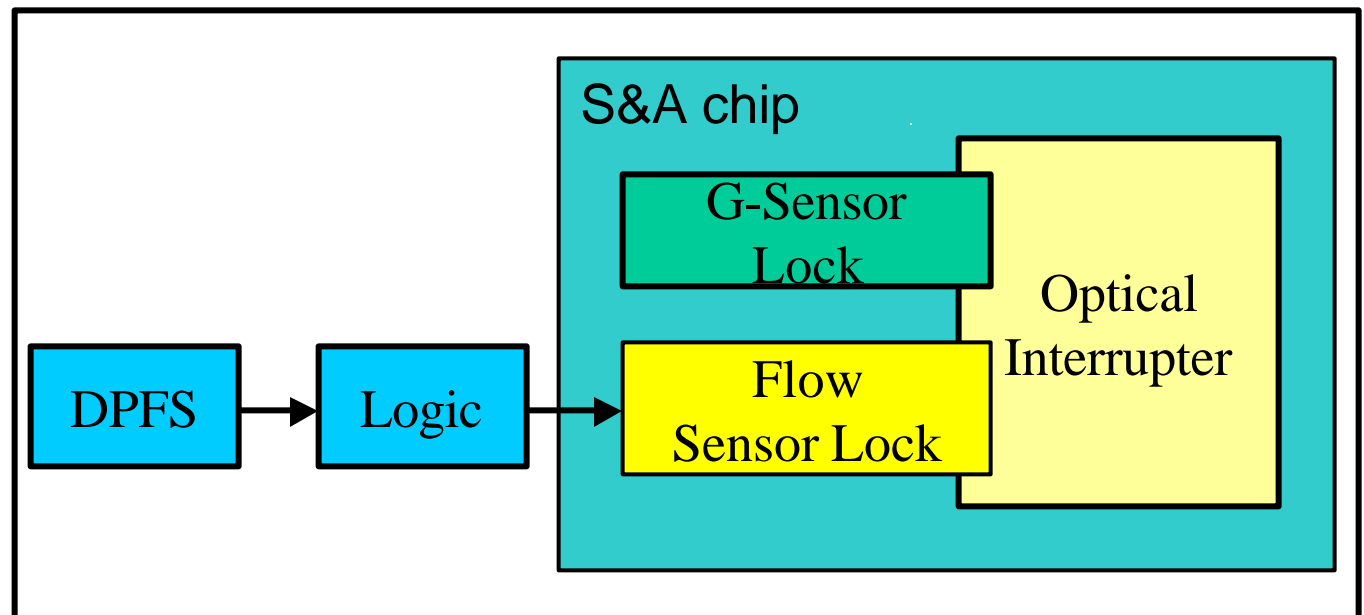
## *Torpedo Application*

DPFS signals an actuator to remove a lock on the slider:  
sensor NOT direct acting

### CCAT MEMS S&A

1<sup>st</sup> environment  
Torpedo launch

2<sup>nd</sup> environment  
Water flow

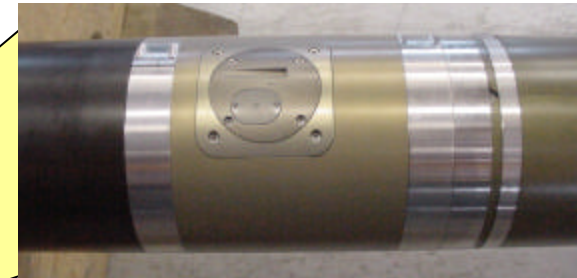


# *Differential Pressure Flow Sensor*

## *Torpedo Application*

### *6.75 inch Canistered Countermeasure Anti-torpedo Torpedo (CCAT)*

- Selected as environmental (flow) sensor for safety and arming (S&A) device
- Selected to supplement/validate axial accelerometer of S&A inertial measurement unit

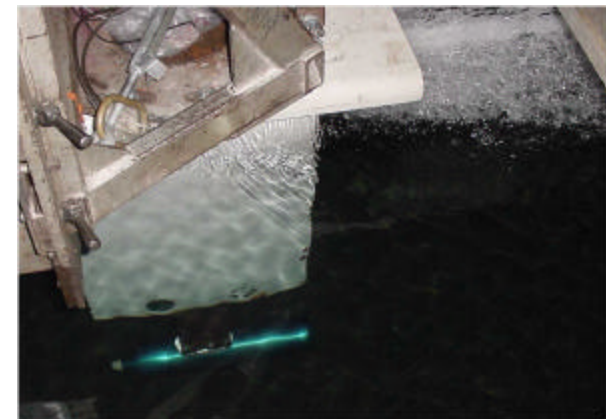


*S&A with DPFS*



### *Extensive laboratory & field testing*

- Operational environments (e.g., temperature, pressure, etc.)
- Indian Head flow simulator
- Torpedo at-sea demonstrations
- Carderock tow tank



# *Differential Pressure Flow Sensor At Sea Demonstrations*

*Several tests were conducted on torpedo trials*

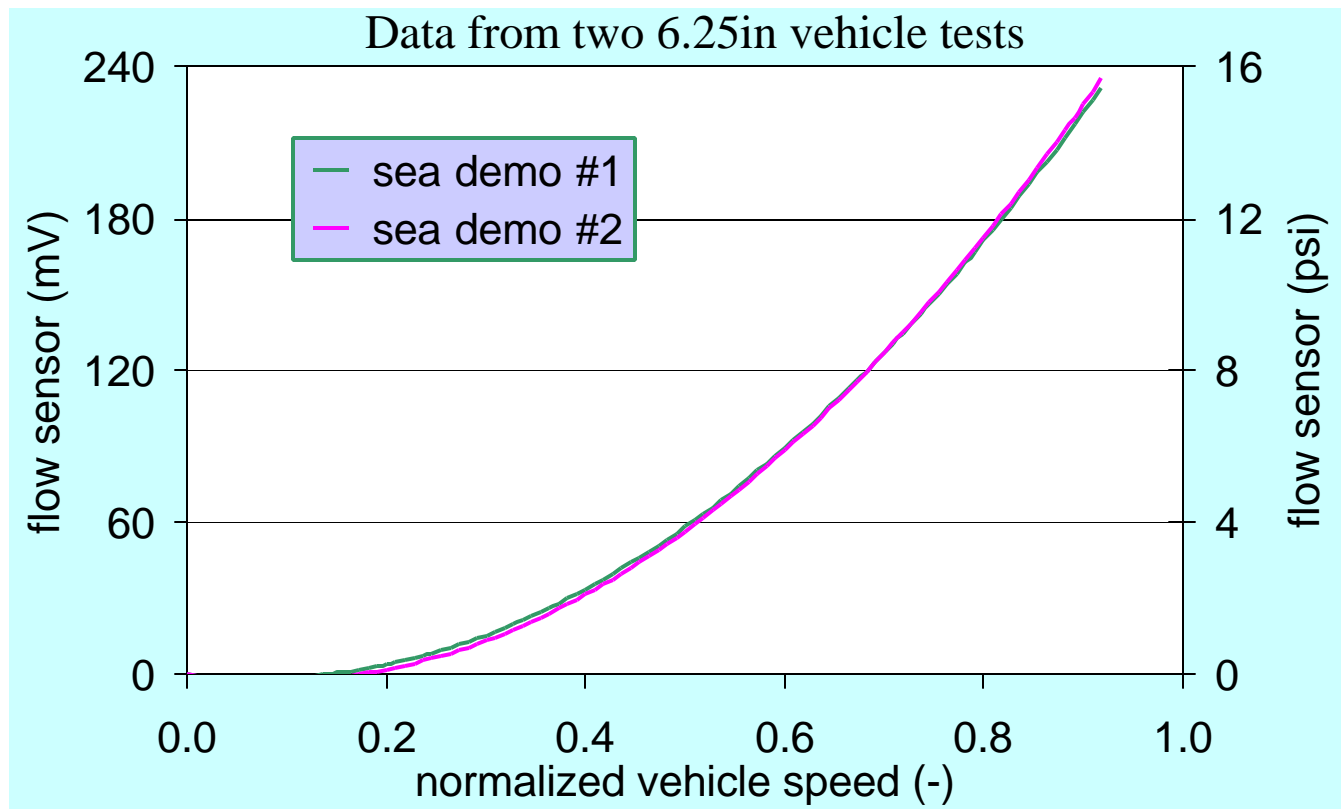
*Test variables:*

Depth

Speed

Acceleration

Turn rate



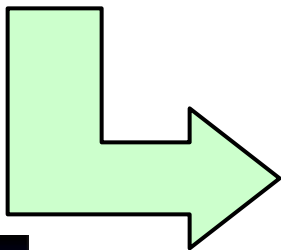
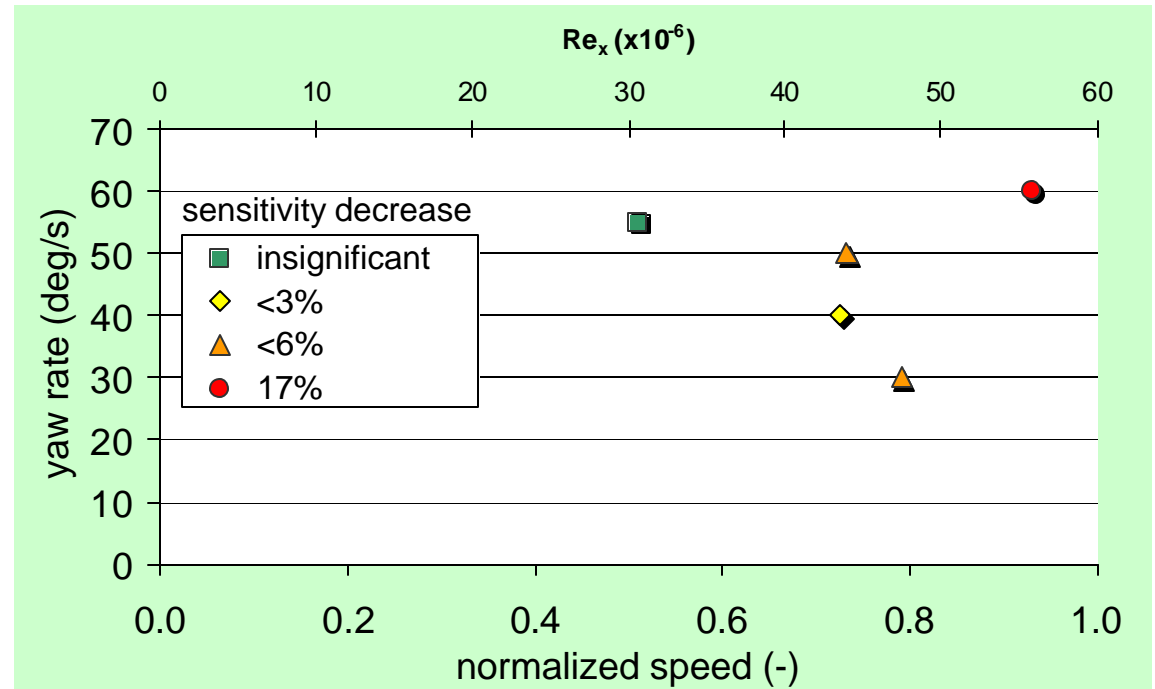
**Flow sensor calibration curves across two sea runs agree extremely well**

# At Sea Demonstrations

## Turn Rate Sensitivity

- *Low speed-high turn rate*
- Insignificant sensitivity changes
- *High speed-high rate maneuvers*
- Flow field disrupted
- Sensitivity decreases
- Output at high speed large
  - Parabolic response
  - Response remains well above noise floor

Effects of speed and turn rate on sensitivity



- Flow environment easily detected
- Sensitivity drop due to maneuvers insufficient to merit loss of environment

# *At Sea Demonstrations*

## *Flow Sensor Performance*

- Flow sensor exhibited excellent response to flow (15psi)
- Parabolic fits (calibration) between flow sensor and vehicle speed fairly accurate ( $R^2 > 0.98$ )
- Calibration curves from each sea run agreed extremely well
- Flow sensor proved suitable as post launch environmental sensor to meet weapon safety criteria
  - Sensor output at low speeds well above noise floor
  - Sensor output loss at high speed, high turn rate insufficient to merit loss of flow environment detection

# *Differential Pressure Flow Sensor*

## *Non-Torpedo Applications*

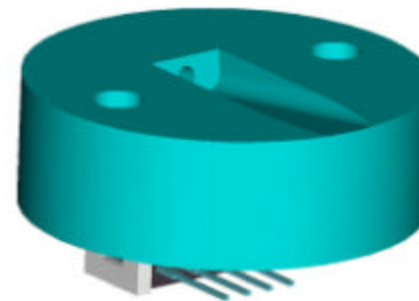
### *Commercial applications*

- Licensed for marine, pipe flow, aeronautical and automobile fields of use
- Commercially available from Wickford Technologies for marine use
- Pipe flow product in development

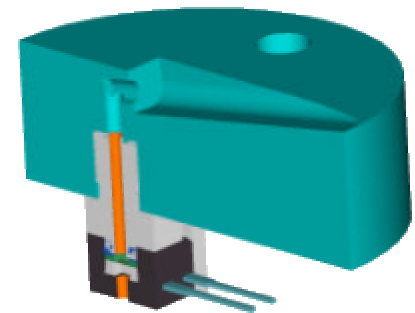


### *Military applications*

- Safety and Arming (environment detection)
  - Missiles/Rockets
  - Gun rounds (non-spinning)
- Inertial measurement units (IMUs)
- Speed indication
  - Aircraft
  - Marine vessels
  - Autonomous vehicles



*Solid model*



*Solid model:  
cross section*

# *Differential Pressure Flow Sensor*

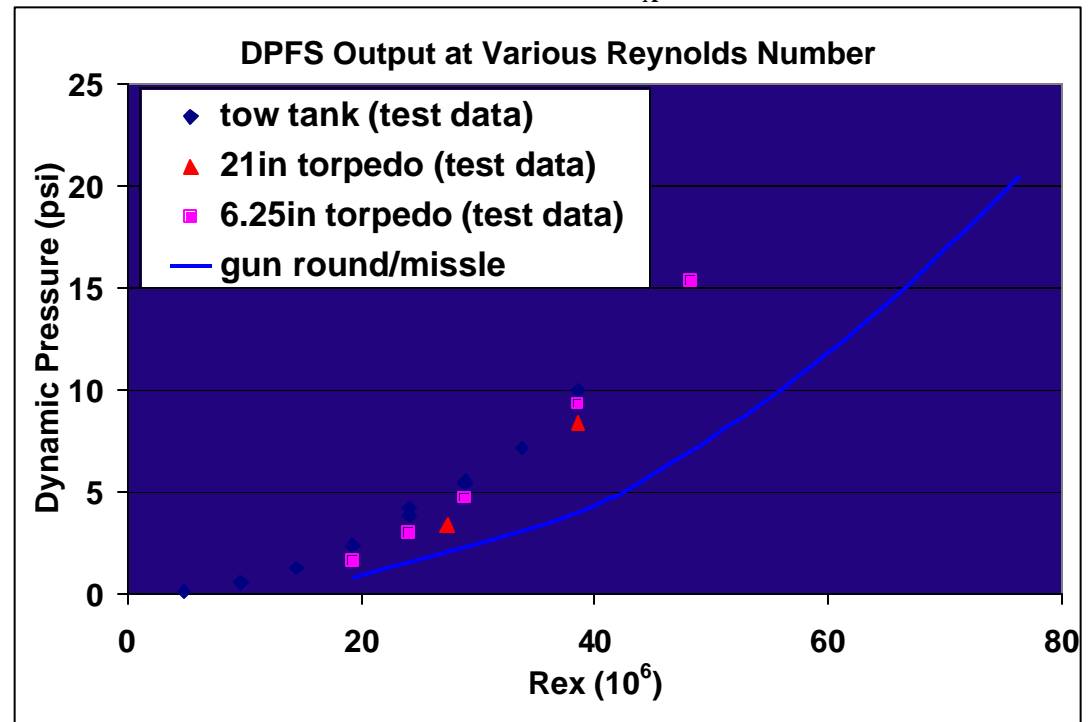
## *Utility in Various Flow Fields*

### *In water tests*

- Span nearly 3 order of magnitude of Reynolds number,  $Re_x$
- Flow tunnel
- Torpedo
- Tow carriage
- Boat

### *Air environments*

- Demonstrated in air gun test
- Air kinematic viscosity 1/16 of water: lower  $Re_x$  for a given flow speed
- High speed air applications (e.g., gun rounds)
  - $Re_x$  in characterized range
- Low speed air flow requires higher resolution pressure sensor





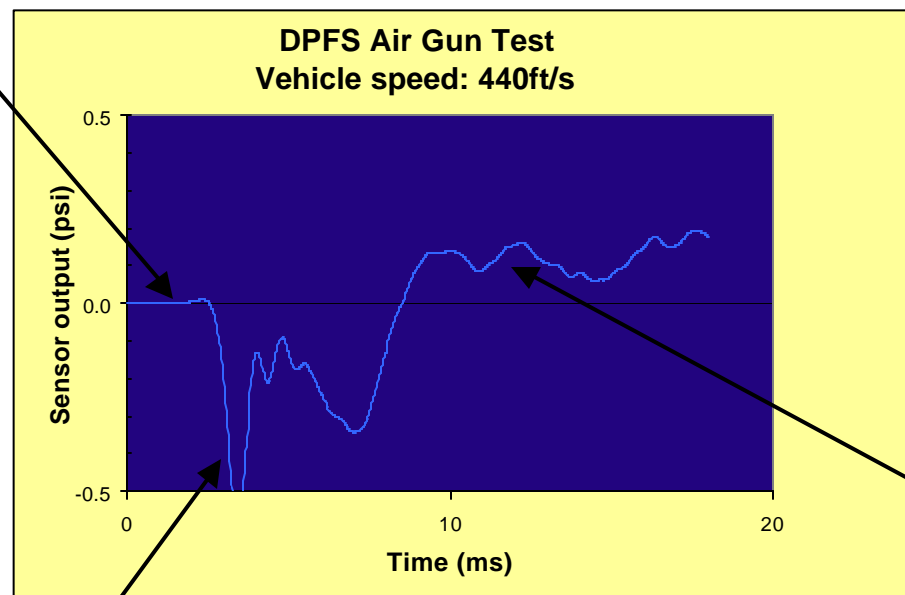
# *Differential Pressure Flow Sensor Air Gun Tests*

*Conducted several instrumented air gun tests*

- Speeds up to 500ft/s
- Sensitivity approached that of Pitot tubes
- All sensors survived launch environments

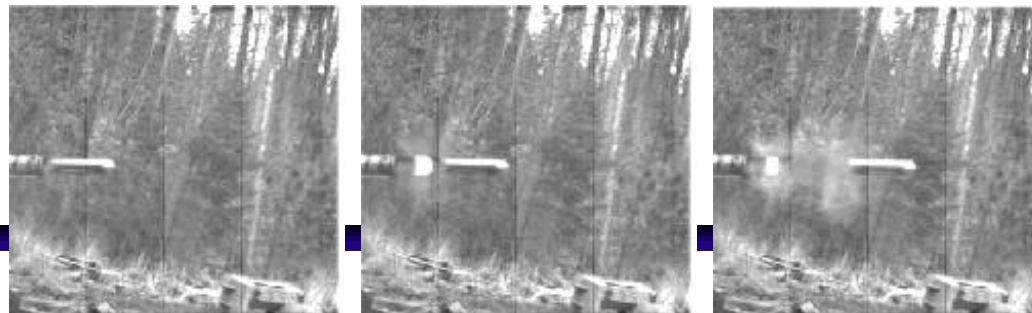


Tube exit



Sustained Flight

Blow by



# *Differential Pressure Flow Sensor*

## *Second Environment for Gun Fire Fuzing*

**Suitable as the 2<sup>nd</sup> environmental sensor for non-spinning rounds**

Desirable features include

- Small (1in<sup>3</sup> non-optimized; 0.3in<sup>3</sup> demonstrated)
- Lightweight
- Low power (<25mW)
- Low cost (\$15/sensor element)
- Simple processing electronics



Adaptation to gun rounds

- $Re_x$  number for gun round/missile application overlaps prior field tests
- Revisit pressure sensor selection
- Assess survivability in gun launch environment

# *Differential Pressure Flow Sensor*

## *Summary*

- Non-intrusive bulk fluid speed measuring device
- Cheap, miniature, low-power MEMS package
- Performs well in air or water
- S&A post launch environment sensor for Canistered Countermeasure Anti-torpedo Torpedo (CCAT)
- Demonstrated over nearly 3 orders of magnitude of Reynolds number
- Licensed and commercialized for boating use

**Suitable 2<sup>nd</sup> environmental sensor for torpedo, missile, and gun round applications**